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CIRCUITRY FOR A HIGH  
VOLTAGE LINEAR CURRENT SENSE IC

This application claims the benefit of U.S. Provisional Application Serial No. 60/130,648 filed April 23, 1999, U.S. Provisional Application Serial No. 60/166,727 filed November 22, 1999, and U.S. Provisional Application Serial No. 60/166,728 filed November 22, 1999.

BACKGROUND OF THE INVENTION

1. Field of the Invention:

The present invention relates to circuitry for a high voltage integrated circuit (IC), and, more specifically, to a differential amplifier circuit that can amplify a differential signal in the hundreds of millivolts near the high voltage power supply, minimize inherent temperature offset drift, and generate a high side current reference in a current sense IC.

2. Description of the Related Art:

The circuitry of a high voltage current sense IC, such as the IR2171 current sense IC sold by International Rectifier Corporation of El Segundo, California, are disclosed in U.S. Patent Application Serial No. 09/266,822 filed March 12, 1999, the entire disclosure of which is incorporated herein by reference.

The IR2171 provides a circuit for transferring static or time variable analog information without electrical isolation from a first (source) reference potential to a second (destination) reference potential.

More specifically, the IR2171 circuit recovers an input signal at a first potential which is offset by a common mode displacement from a second potential. The circuit in its most basic form includes: (1) circuitry for converting the input signal at the first potential to a pulse width modulated signal; and (2) circuitry for level shifting the pulse width modulated signal from the first potential to the second potential. The IR2171 advantageously can be used in a motor controller for transferring information relating to current flow through a high side resistor from a high voltage potential to a lower level potential for conditioning and processing the information.

Desirable features for a high voltage current sense IC, such as the IR2171, include a differential amplifier that can amplify a differential signal in the hundreds of millivolts near the power supply, minimize inherent temperature offset drift, and generate a high side current reference.

Fig. 1 shows a typical prior art differential amplifier circuit 2. Circuit 2 includes a differential amplifier 4 biased by four matching resistors 6, 8, 10, and 12. The advantage of the prior art differential amplifier circuit, such as the circuit shown in Fig. 1, is that  $V_{in}$  can be amplified with a CMIV (common mode input voltage) from  $V_{SS} = -1V$  to close to  $V_{DD}$ .

The disadvantages of the circuit of Fig. 1 include the following: (1) four matching resistors 6, 8, 10, and 12 are required; (2) the four resistors occupy valuable space on the die; (3) the CMRR (common mode rejection ratio) depends on how closely the resistors are matched, which is typically not better than 1% in an IC implementation; (4) the offset also depends on how closely the resistors are matched; and (5)  $V_{ref}$  which needs to supply current in 10 and 12, should have a low

impedance output; in practice,  $V_{ref}$  is implemented as a voltage reference and follower op-amp 14, as shown in Fig. 2.

Fig. 3 shows another prior art differential amplifier circuit 16. Circuit 16 includes differential amplifier 18, resistors 20 and 22, and provided with a  $V_{ref}$  24. The advantages of circuit 16 of Fig. 3 are as follows: (1) only two resistors 20 and 22 need be matched, which is much easier and results in a CMMR of better than 0.5%; (2) the CMRR is improved with respect to circuit 2 of Fig. 1, and the offset is better, both due to the reduced number of resistors required (resulting in improved resistor matching); and (3)  $V_{ref}$  is a high impedance load, and therefore be a simple resistor divider; since there is no need for the buffer of Fig. 2, the circuit occupies a small area. The disadvantage of circuit 16 of Fig. 3 is that it can only have a CMIV of  $V_{SS}$ , since  $V_{in}$  is referenced to  $V_{SS}$ .

A further shortcoming of the prior art is that conventional op amps have an input offset voltage which is temperature sensitive. It would be desirable to provide an op amp circuit in which the input offset voltage is constant and independent of changes in temperature.

High voltage current sense ICs require a high side current reference. Referring to Fig. 4, this is typically accomplished by providing an NPN transistor 22 which has its collector tied to a  $V_B$  supply. As described more fully below, by regulating the voltage of emitter resistor 24 of the NPN transistor and repositioning resistor 24, a  $\Delta V_{be}/R$  current reference can be implemented on the high-side. Very good tolerance ( $\pm 10\%$ ) and power supply rejection ratio has been implemented using this approach.

### SUMMARY OF THE INVENTION

The present invention advantageously provides a differential amplifier circuit for a current sense IC which overcomes the disadvantages of the prior art circuits discussed above and can amplify a differential signal in the hundreds of millivolts near the power supply. In addition, the circuit of the present invention generates a constant current using opposing minus temperature coefficient MOSFETs. Accordingly, the invention provides an op-amp circuit with an input offset voltage which is constant and insensitive to temperature changes. The invention also advantageously provides a circuit for generating a current reference on the high side of the current sense IC.

Other features and advantages of the present invention will become apparent from the following description of the invention which refers to the accompanying drawings.

### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a diagram of a differential amplifier circuit according to the prior art.

Fig. 2 is a diagram of a voltage reference and follower op-amp circuit according to the prior art.

Fig. 3 is a diagram of another differential amplifier circuit according to the prior art.

Fig. 4 is a diagram of a typical prior art high side current reference circuit for a high voltage current sense integrated circuit.

Fig. 5 is a block diagram of a current sense integrated circuit according to the present invention.

Fig. 6 is a functional block diagram of a pulse width modulator circuit according to the present invention.

Fig. 7 is a diagram of a differential amplifier circuit according to the present invention.

Fig. 8 is a diagram of an integrated circuit implementation of the differential amplifier circuit of Fig. 7.

Fig. 9 is a diagram of a PMOS op amp circuit with minimized temperature drift according to the present invention.

Fig. 10 is a graph illustrating drift current in the circuit of Fig. 9.

Fig. 11 is an elevation of an NPN transistor layout according to the present invention.

Fig. 12 is a schematic illustration of an NPN transistor according to the present invention.

Fig. 13 is a circuit diagram of a high side current reference according to the present invention.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to Fig. 5, a block diagram of the circuitry of a high voltage current sense IC **30** according to a preferred embodiment of the present invention is shown. The signal of interest VSP is first input to a differential amplifier (Pamp) **32** for buffering and amplification as necessary. Other offset adjustments may be performed as required. Reference voltage generating circuitry **34** provides the input VREF to PAMP **32**, as well as to other sections of the IC. Current reference **35** is also provided.

The amplified signal from Pamp 32 is converted from analog to pulse form using pulse-width modulation encoding. In a preferred embodiment of the invention, a sawtooth generator 36 outputs a high frequency (e.g., 40kHz) waveform (the sawtooth generator may, if desired, be replaced with a triangle wave generator). The output of pulse width modulator PWM 38 is a pulse width modulated waveform, in which the width of the pulses represents the voltage VSP.

PWM 38 output is fed to pulse generator 40 which produces a rising edge triggered pulse and a falling edge triggered pulse. These pulses are transposed to a lower potential through MOSFETs 42 and 44, and low side conversion circuit 46. Recovery of the digital PWM data is performed at the lower reference potential.

### **PWM Circuit**

Fig. 6 shows a more detailed block diagram of PWM circuit 38. PWM circuit 38 includes pcomp circuitry 50, level shift circuitry contained in block 52, and digital circuitry 53 including NOR gate 54, inverter 56, and NOR gates 58 and 60.

### **PAMP**

Referring to Fig. 7, a differential amplifier circuit 70 according to the present invention is shown being implemented in the IR-2171 current sense IC. Differential amplifier circuit 70 includes differential amplifier 72 and matched resistors 74 and 76. VREF 78 is provided by reference circuitry 34 (Fig. 5). Differential amplifier circuit 70 has all of the advantages of the prior art circuit of Fig. 3, but in addition, assuming  $V_{DD} = 15V$ , the CMIV has an increased range from  $V_{SS} = -5V$  (increased compared to the circuits of Figs. 1 and 3) to  $V_{SS} = +5V$ .

In the circuit **70** of Fig. 7, the CMIV cannot go to VDD, as compared to the circuit of Fig. 1; however, this feature is unnecessary in high voltage current sense ICs such as the IR2171. In addition, at least one more decoupling capacitor (not shown) is required from VSN to VB, as VSN is now the supply return for the analog section of the IC. An IC implementation of the circuit **70** of Fig. 7 is shown in Fig. 8, in which differential amplifier **72** has been replaced by a PMOS operational amplifier **80**, as described more fully below.

#### **Circuit to minimize temperature offset drift -- POPAMP**

Fig. 9 is a more detailed circuit diagram of PMOS op amp **80** of the present invention, which has an input voltage which is temperature insensitive. According to a preferred embodiment, op amp **80** forms part of PAMP **70** shown in Fig. 7 discussed above.

Referring to Fig. 9, Popamp circuit **80** is provided with mirrored or opposing MOSFETs **82**, **84** such that the offset voltage of the circuit is the difference between the gate-to-source voltage ( $V_{gs}$ ) of MOSFETs **82** and **84**. Matching MOSFET devices **86** and **87** are provided to ensure equal current capabilities and biasing of MOSFETs **82** and **84**. W/L for MOSFET **87** is set for saturation operation. MOSFETs **88** and **89** are matched to ensure the same currents through their branches. MOSFET **89** biases inverting stage **90** with constant temperature independent current. MOSFETs **92** and **94** provided additional gain. Alternatively, using bipolar technology, devices **92** and **94** could be eliminated. In addition, the W/L sizing of MOSFETs **92** and **94** is selected to provide a small output impedance. Capacitors **95** and **96**, and the resistor **98** move right half plane zero to infinity, and maintain good stability of the POPAMP circuit **80**.

If the gate-to-source voltages of MOSFETs 82 and 84 are constant over temperature, the offset voltage should be constant over temperature. Thus, the circuit forces a constant current using the opposing minus temperature coefficient MOSFETs.

The relationship is based on the following formula for ID (drift current) and is shown in the graph of Fig. 10:

$$I_D = k (V_{GS} - V_T)^2$$

$$k = \frac{\mu C_{ox}}{2}$$

where  $C_{ox}$  is the oxide capacitance and both  $V_T$  and  $\mu$  are values which decrease as the temperature increases.

### Current Reference in High Side Well of Chip Driver

A high side current reference is provided according to the present invention by regulating the emitter voltage of the NPN transistor and repositioning the resistor as discussed above in connection with the prior art circuit of Fig. 4, so that the current reference resides in the high side well of the high voltage IC.

The following equations are applicable to the prior art circuit shown in Fig. 4:

$$V_R = \Delta V_{be} = \frac{n \cdot k \cdot T}{9} \ln(X \times N)$$

$$I_{ref} = \frac{V_R}{R}$$



To make  $\Delta V_{be}/R$  close to ideal,  $n$  in the above equation should be 1. A layout 100 for an NPN transistor, shown in Figs. 11 and 12, makes  $n$  as close as possible to 1. In accordance with the present invention, a gate 102 is added to the NPN transistor to enhance the P well surface.

The implementation of the present invention in the prior art circuit of Fig. 4 requires an amplifier that occupies a lot of area. Referring to Fig. 13, the implementation of the present invention in a high voltage current sense IC is identified as current reference 35 (Fig. 5).

Matching transistors 120 and 122 form the  $\Delta V_{be}/R$ . The area ratio is 9:1 and the current ratio, determined by MOSFETs 126 and 128, is 1:5 so that

$$\Delta V_{be} = V_t \ln 45, V_t = \frac{kt}{q}, 45 = 9 \times 5$$

$$\Delta V_{be} \sim 100mV$$

$$I_{ref} = \frac{\Delta V_{be}}{R} = \frac{0.1}{R} A = \frac{100}{R(k\Omega)} \mu A$$

MOSFETs 130, 132, 133, and 136 form the amplifier. The output of the amplifier  $V_{out}$  is the drains of MOSFETs 130 and 136. The configuration is such that  $\Delta V_{be}/R$  is mirrored from the source of MOSFET 132 to analog ground.

Other devices in circuit 35 are provided for startup, stability and to increase power supply rejection ratio. Preferably, in order to approach an ideal result, certain groups of devices are matched: Transistors 120 and 122; MOSFETs

130 and 132; MOSFETs 126, 128, and 138; MOSFETs 134, 136, and 140.

Accordingly,  $\Delta V_{be}$  depends only on the above matching and temperature.

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$$\Delta V_{be} = \frac{kT}{q} \ln (\text{area ratio} \times \text{current ratio}).$$

$I_{ref}$  will then only depend on absolute value of R, as follows:

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$$I_{ref} = \frac{\Delta V_{be}(T)}{R(T)}$$

If  $R(T)$  tracks  $\Delta V_{be}(T)$  with respect to temperature, then  $I_{ref}$  will be independent of temperature, and will depend only on absolute value of R. Using  $P_{body}$  and SP+ to get the correct temperature on R, R can be made to  $\pm 10\%$  accuracy, so  $I_{ref}$  will have  $\pm 10\%$  accuracy (assuming matching and n factor ideal).

A plurality of current reference signals can be provided to various portions of the IC by way of block 150.

Although the present invention has been described in relation to particular embodiments thereof, many other variations and modifications and other uses will become apparent to those skilled in the art. Therefore, the present invention is limited not by the specific disclosure herein, but only by the appended claims.